Multi-Frequency Broadband Optimization of Spaceborne Reflectarrays for Space Applications

Daniel R. Prado[1,2], Manuel Arrebola[1], Marcos R. Pino[1] and George Goussetis[2]

[1] **Universidad de Oviedo**, Spain.
Department of Electrical Engineering. Group of Signal Theory and Comunications.

[2] **Heriot-Watt University**, UK.
School of Engineering and Physical Science. Institute of Sensors, Signals and Systems.

Abstract

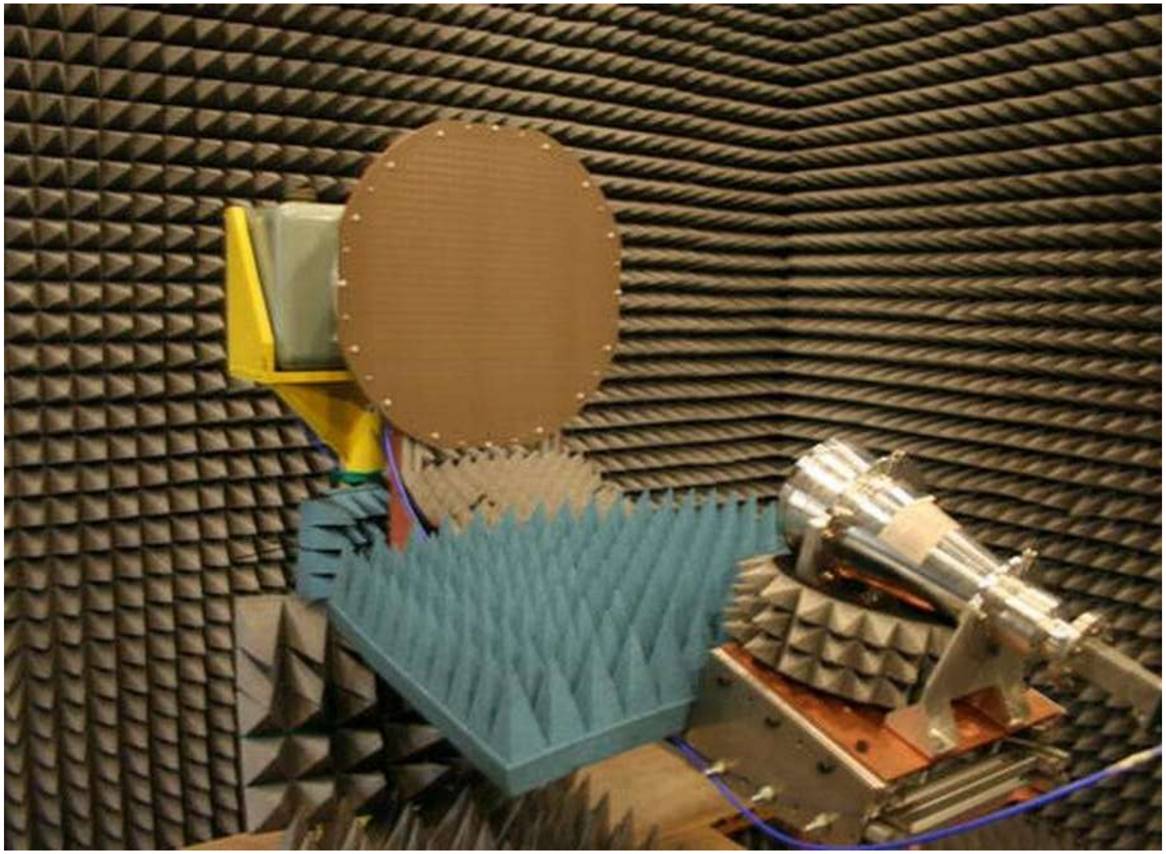
Direct-to-home (DTH) applications usually require a radiation pattern with a given footprint on the surface of the Earth and impose stringent cross-polarization requirements in the form of crosspolar discrimination (XPD) or crosspolar isolation in a given bandwidth. This paper describes a multifrequency broadband optimization procedure and performance results of a very large spaceborne reflectarray for DTH application in a 10% bandwidth. The proposed design methodology is based on the generalized intersection approach and the use of a multi-resonant unit cell with multiple degrees of freedom (DoF). The procedure is divided into three stages to facilitate convergence towards a broadband performance. First, a initial narrowband design at central frequency is obtain. Then, a broadband optimization including XPD requirements is carried out with a limited number of DoF. Finally, more DoF are included in the last stage optimization to obtain a broadband reflectarray with improved cross-polarization performance.

Index Terms:

reflectarrays, optimization, space communications, shaped-beam, generalized intersection approach

Outline

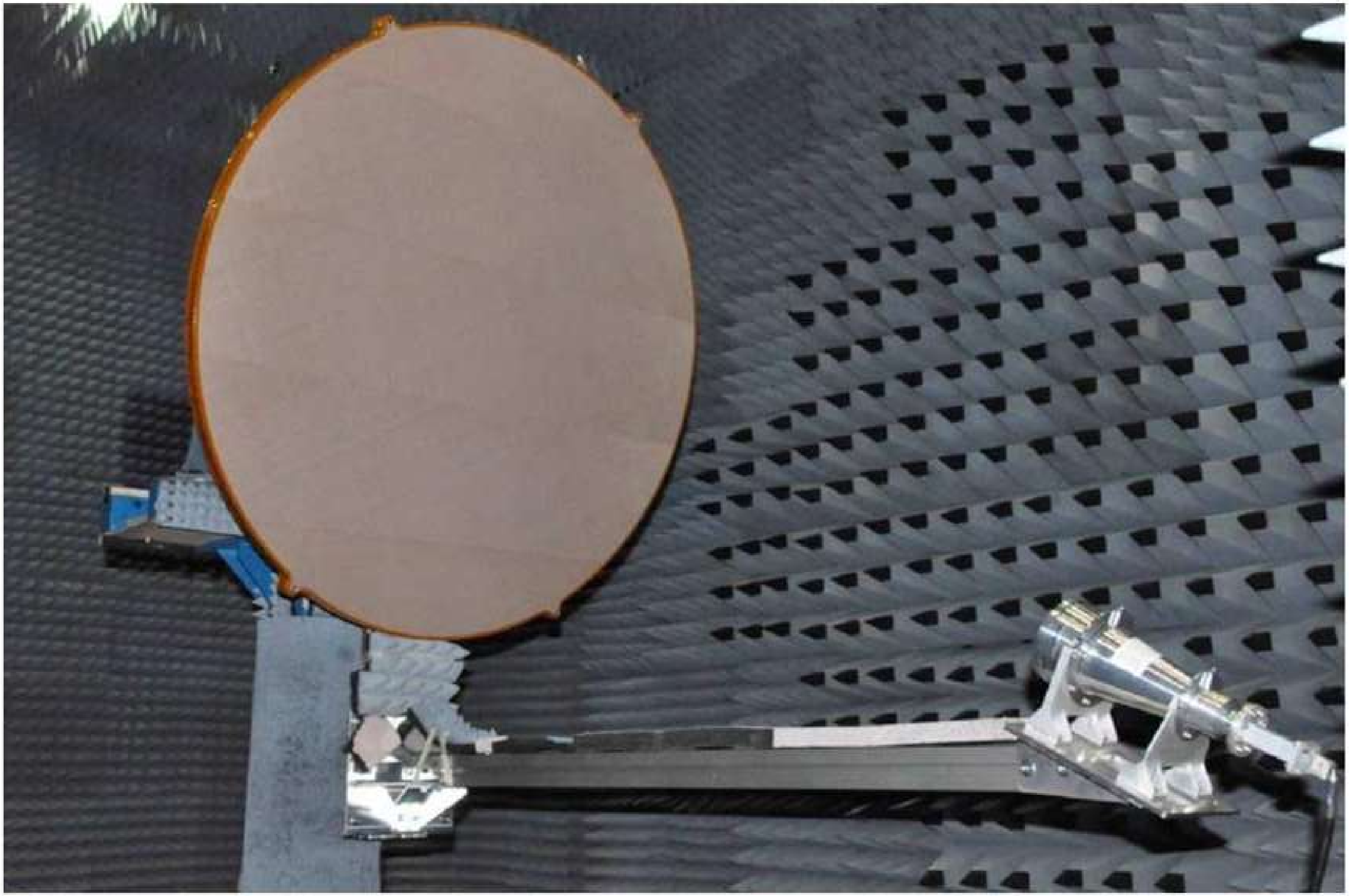
1. Introduction.
2. Design methodology based on the generalized Intersection Approach.
3. Design of a large reflectarray with southern Asia coverage.
4. Conclusion.



Introduction

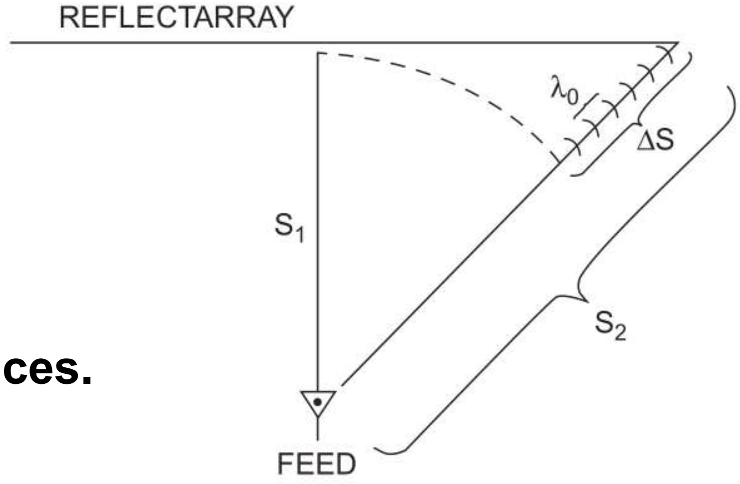
Introduction

- **Goal:** broadband reflectarrays with enhanced performance for space missions with tight requirements.



Introduction

- Planar reflectarrays are inherently narrow-bandwidth mainly for two reasons [1]:
  - Narrow bandwidth of resonant elements.
  - Differential spatial phase delay.



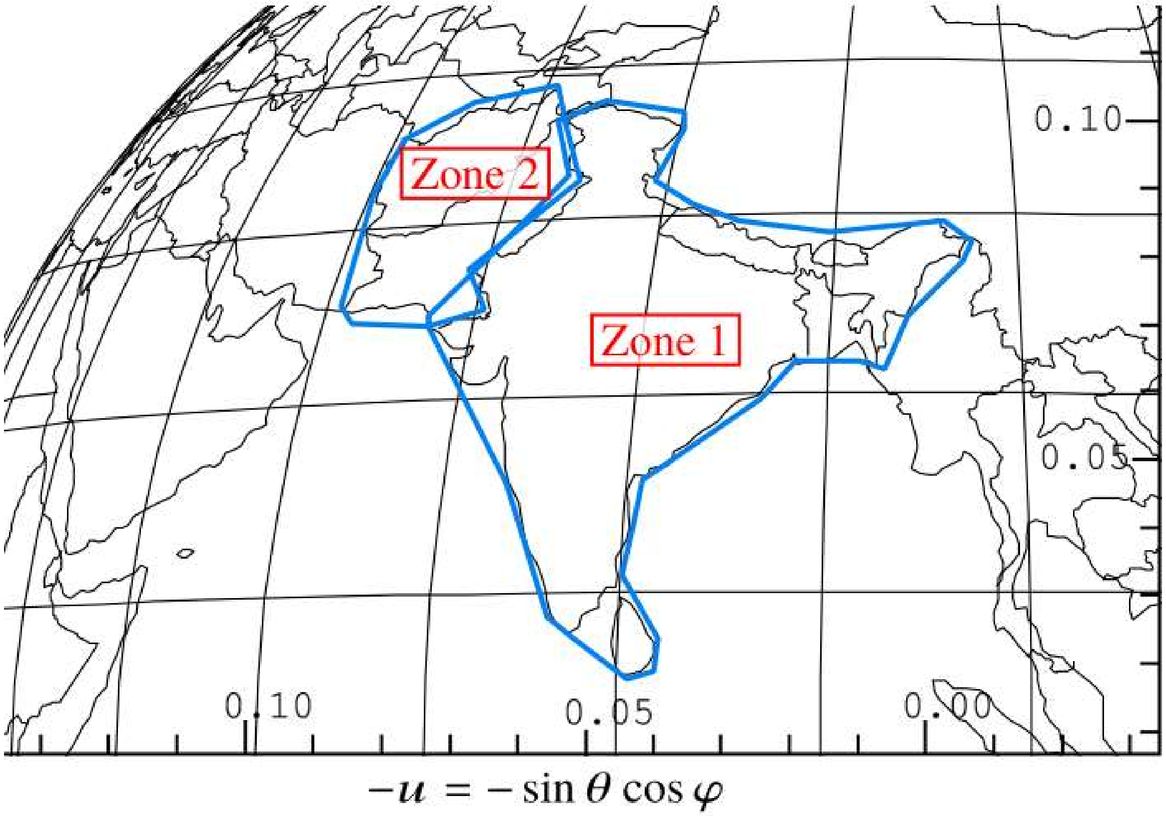
- Solutions for the first limitation:
  - **Broadband elements with multiple resonances.**
  - Subwavelength elements.
- The differential spatial phase delay may be overcome by:
  - **Adjusting geometry of the unit cell at several frequencies.**
  - Using true time delay reflectarray elements.
  - Increasing the f/D ratio.
  - Using curved or faceted reflectarrays.

[1] J. Huang and J. A. Encinar, Reflectarray Antennas. Hoboken, NJ, USA: John Wiley & Sons, 2008.

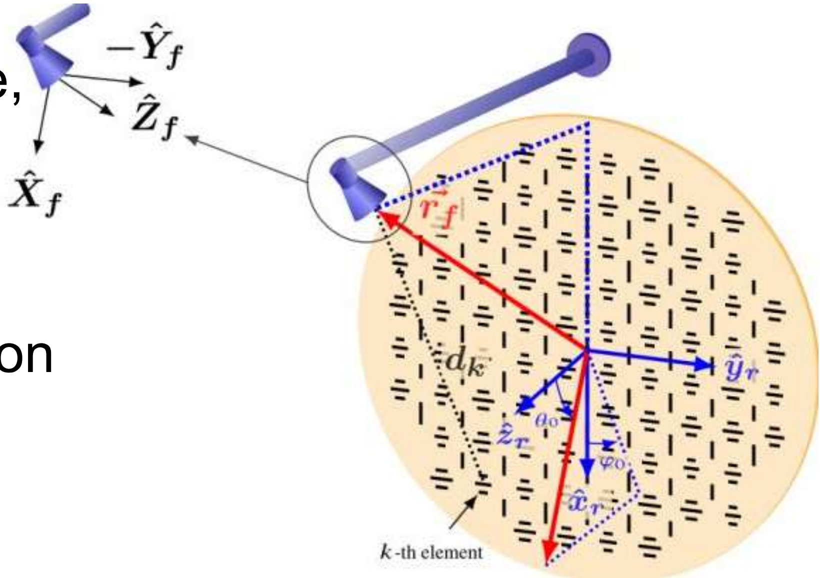
Introduction

- Several techniques have been proposed for the crosspolar optimization at the element level:
  - Suitable arrangement of elements, reduction of undesired tangential field, element rotation…
  - They provide suboptimal results.
- A better approach (although computationally more expensive) is the direct optimization of the layout.
  - All reflectarray elements are optimized at the same time.
- Here we will employ a method of moments based on local periodicity (MoM-LP) in a wideband optimization procedure for an accurate analysis and optimization of reflectarray antennas.
- We present a design of a very large reflectarray antenna:
  - Wideband reflectarray with southern Asia coverage (11% relative bandwidth).
  - Cross-polarization requirements in the form of XPD are considered.

Design methodology



Overview of reflectarray analysis



- Feed generates $\vec{E}_{inc}^{X/Y}(f)$ on reflectarray surface, which depends on frequency.
- $\vec{E}_{ref}^{X/Y}(f)$ is the field reflected by the elements.
- Both fields are related through matrix of reflection coefficients $R(f)$ at each element:

$$\vec{E}_{ref}^{X/Y}(f) = R(f) \cdot \vec{E}_{inc}^{X/Y}(f)$$

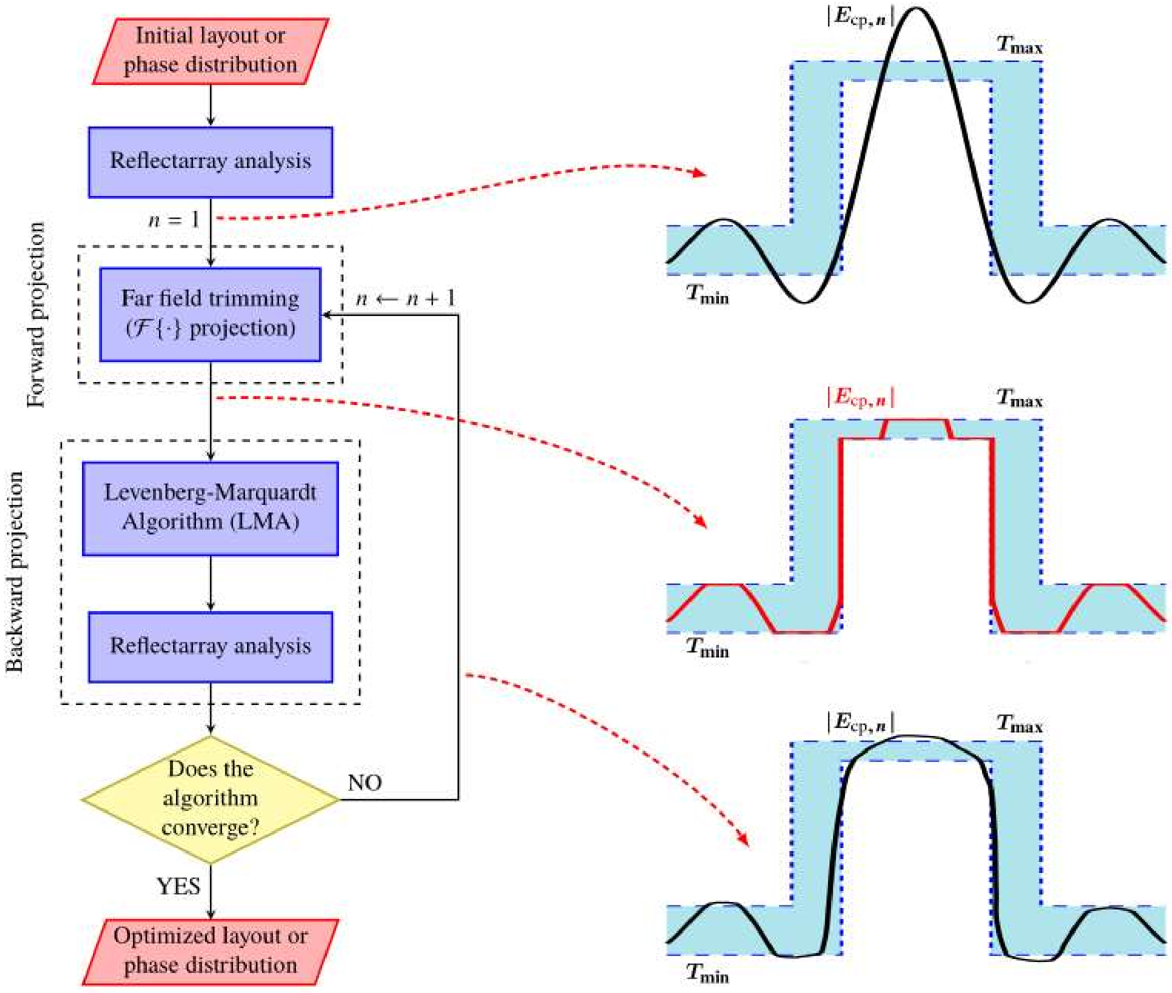
- $R(f)$ fully characterizes the behaviour of the unit cell.

$$R(f) = \begin{pmatrix} \rho_{xx}(f) & \rho_{xy}(f) \\ \rho_{yx}(f) & \rho_{yy}(f) \end{pmatrix}$$

- $R(f)$ is computed with a FW-LP tool. In our case, MoM-LP in spectral domain [2].
- Far field is the Fourier transform of reflected tangential field.

[2] R. Florencio, R. R. Boix, and J. A. Encinar, “Enhanced MoM analysis of the scattering by periodic strip gratings in multilayered substrates,” IEEE Trans. Antennas Propag., vol. 61, no. 10, pp. 5088–5099, Oct. 2013.

Wideband design procedure



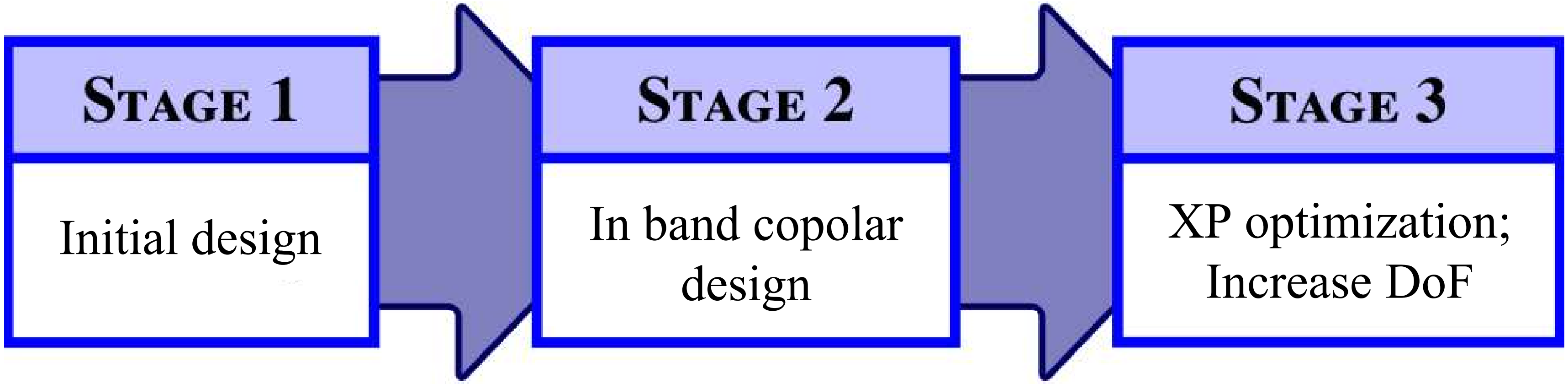
- Based on generalized Intersection Approach [3].
- Two operations per iteration:
  - Forward projection.
  - Backward projection (LMA).
- For the multi-frequency optimization, the functional minimized in the backward projector is:

$$F = \sum_{f=1}^{N_f} \sum_{m=1}^{M} \Big\{ W_{f,1}(\vec{r}_m) \big[\mathrm{CP}'_{\min,f}(\vec{r}_m) - \mathrm{CP}_{\min,f}(\vec{r}_m; \bar{\xi}) \big] + W_{f,2}(\vec{r}_m) \big[\mathrm{XPD}'_{\min,f}(\vec{r}_m) - \mathrm{XPD}_{\min,f}(\vec{r}_m; \bar{\xi}) \big] \Big\}^2,$$

[3] D. R. Prado, et al., "Efficient crosspolar optimization of shaped-beam dual-polarized reflectarrays using full-wave analysis for the antenna element characterization", IEEE Transactions on Antennas and Propagation, vol. 65, no. 2, pp. 623-635, Feb. 2017.

Wideband design procedure

- The wideband design procedure is divided in several stages to improve convergence.



STAGE 1

Initial design

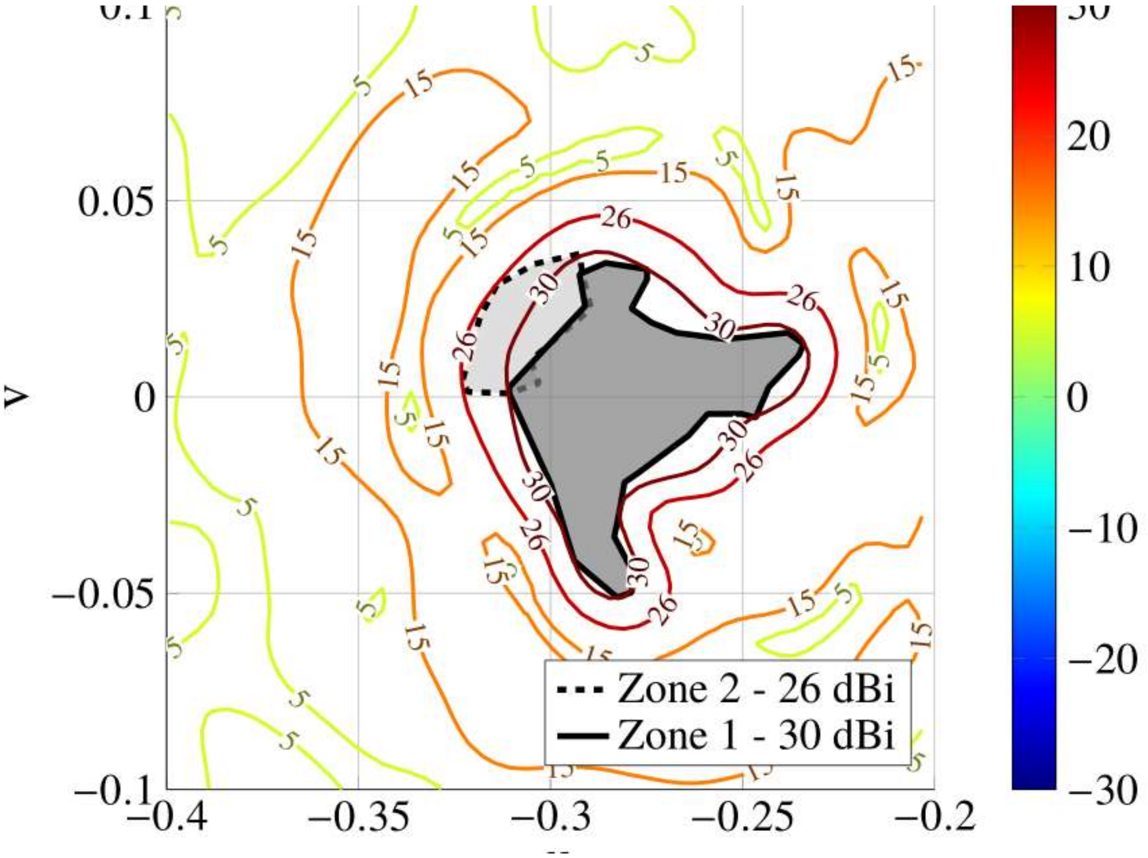
STAGE 2

In band copolar design

STAGE 3

XP optimization; Increase DoF

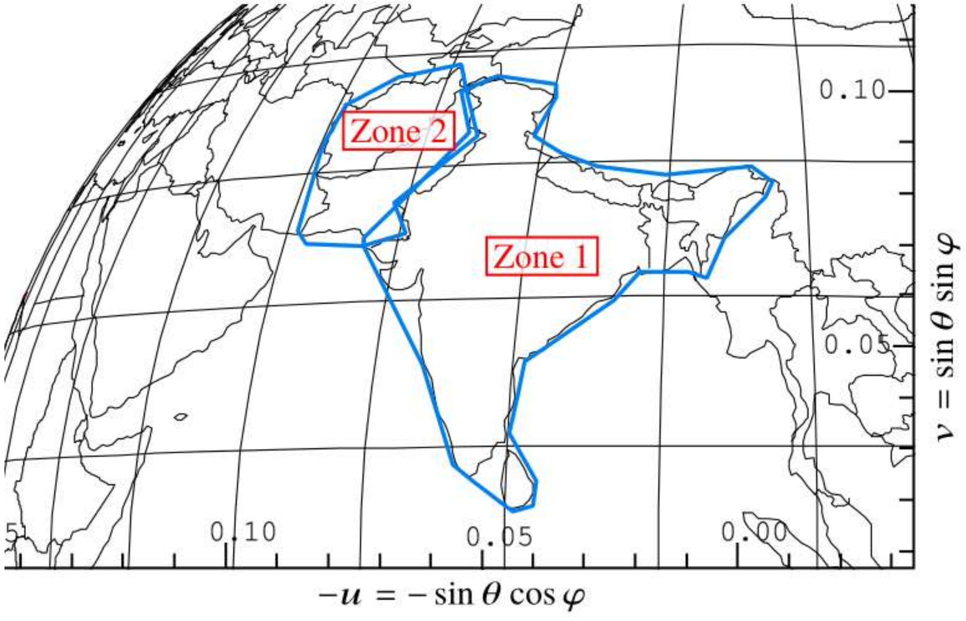
- First stage is an initial design (typically at central frequency).
  - Rest of stages can be intertwined.
- There can be more stages.
  - E.g. optimize each polarization independently.
- Controlled wideband design procedure using an existing algorithm.



Design results

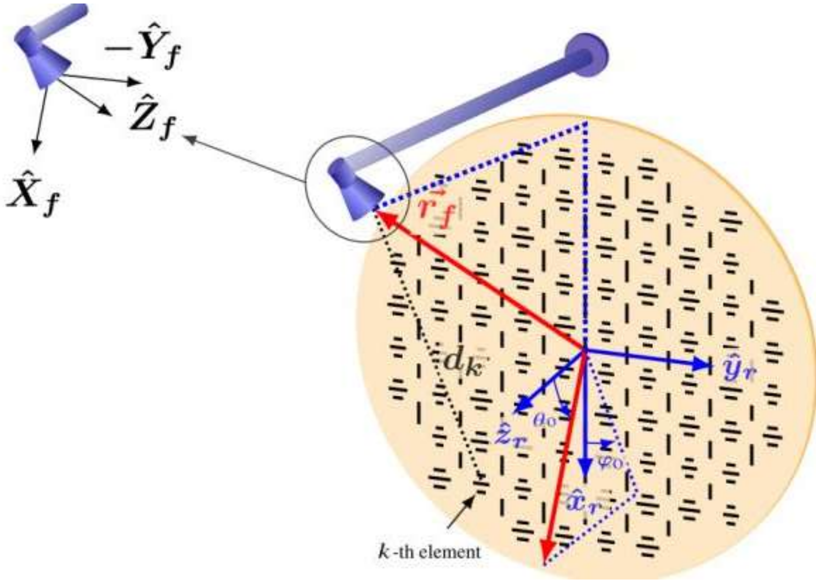
Requirements

- Southern Asian footprint with two coverage zones.
    - Specifications of SES-12 satellite.
- 11% bandwidth (11.80 — 13.20 GHz).
- Minimum copolar gain of 30 dBi in zone 1 and 26 dBi in zone 2.
- XPD_{min} of 33 dB in both zones.



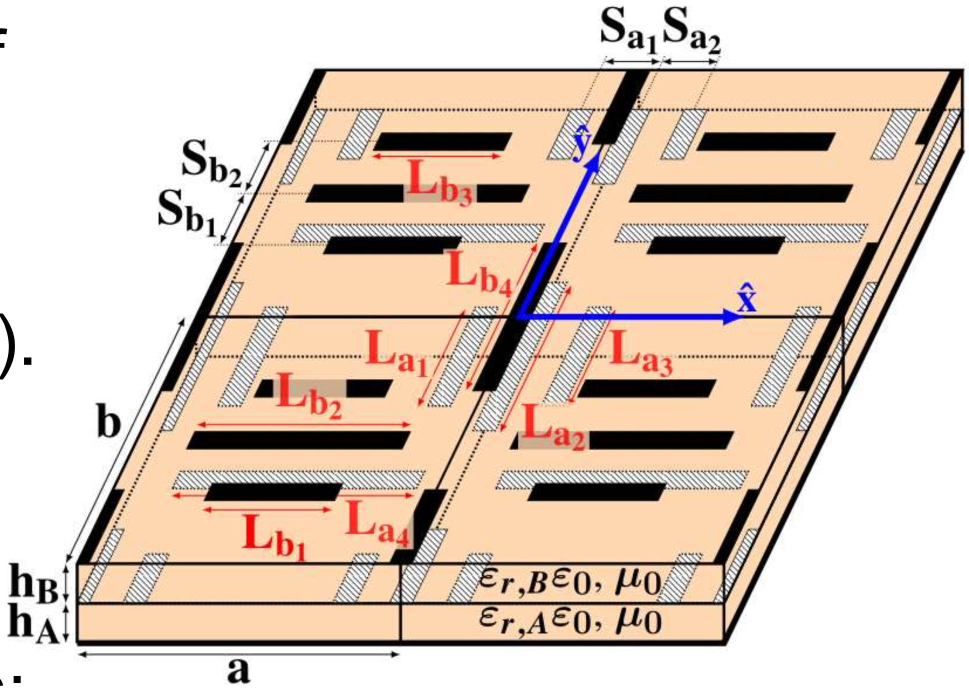
Antenna characteristics

- Single-offset reflectarray antenna.
- Elliptical with 6640 elements (94×90).
- Periodicity: 12 mm × 12 mm ($0.5\lambda_0$).
- Illumination taper between −16.1 dB and −17.9 dB in the range [11.80, 13.20] GHz.
- Feed placed at (−353, 0, 1062) mm.
- Satellite in geostationary orbit at 95º E longitude.



Unit cell and DoF

- Unit cell is based on two sets of parallel and coplanar dipoles in two layers of metallization.
- **Layer A:** Arlon AD255C (93 mil).
- **Layer B:** Diclad 880 (60 mil).



- 2 DoFs in the 1st and 2nd stages:
  - T_x and T_y from which the dipoles lengths are obtained:

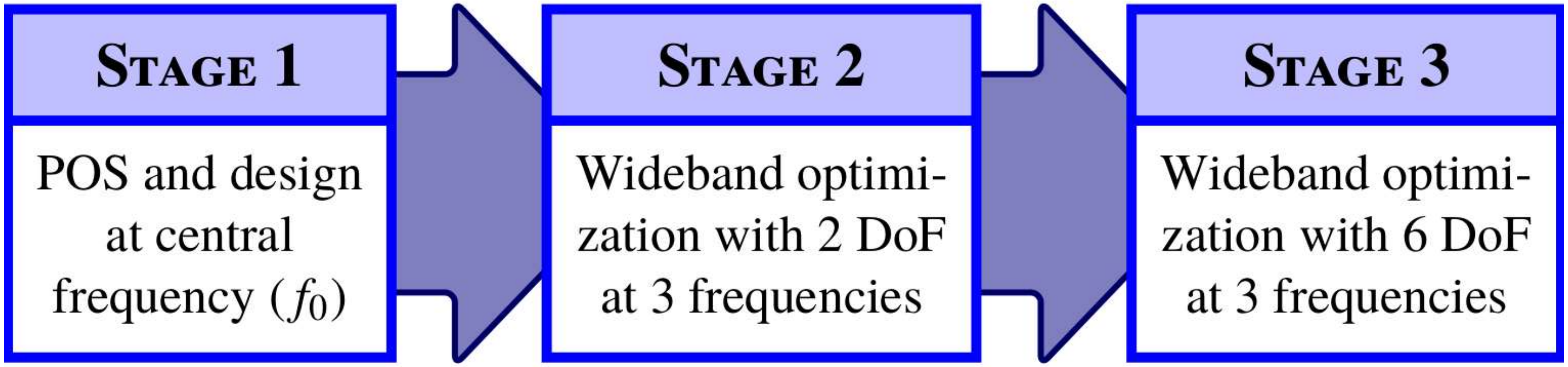
$$L_{a_4} = T_x; \quad L_{b_1} = L_{b_3} = 0.63T_x; \quad L_{b_2} = 0.93T_x$$

$$L_{b_4} = 0.95T_y; \quad L_{a_1} = L_{a_3} = 0.58T_y; \quad L_{a_2} = T_y$$

- 6 DoF in 3rd stage:
  - All dipole lengths, keeping equal the lateral dipoles.

Wideband design strategy

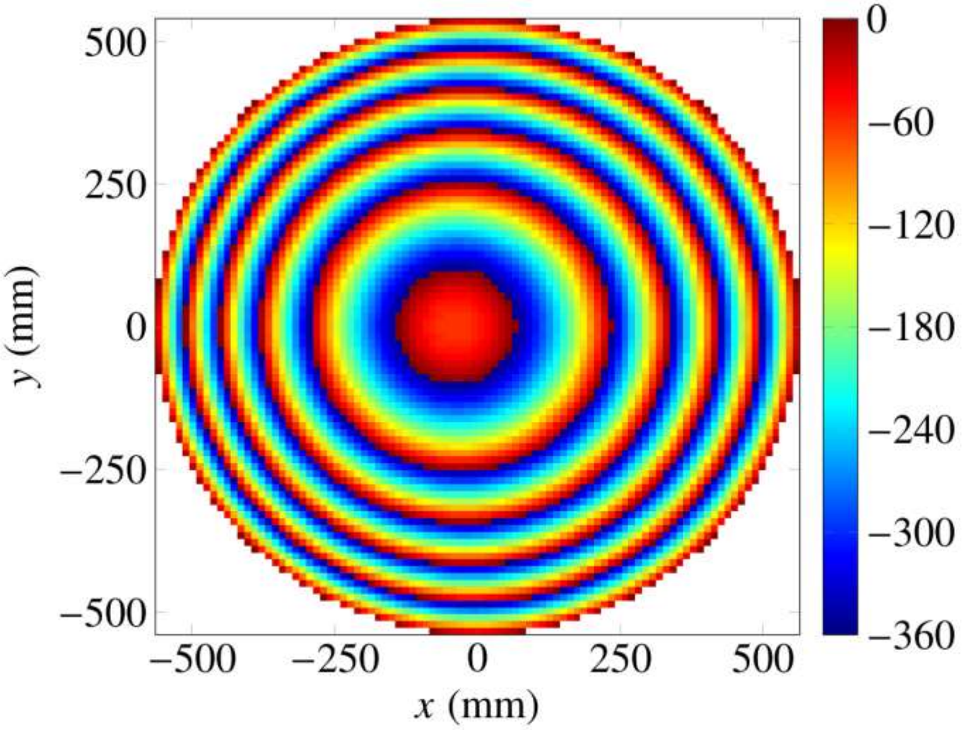
- Wideband design in three stages:
  1. **Central frequency design.**
     - ○ POS and layout design at 12.50 GHz.
  2. **Copolar-only wideband optimization @ 11.80, 12.50 and 13.20 GHz.**
     - ○ Using 2 degrees of freedom (DoF) per element (T_x and T_y).
  3. **Wideband crosspolar optimization @ 11.80, 12.50 and 13.20 GHz.**
     - ○ Number of DoF per element increased to 6 (keeping cell symmetry).



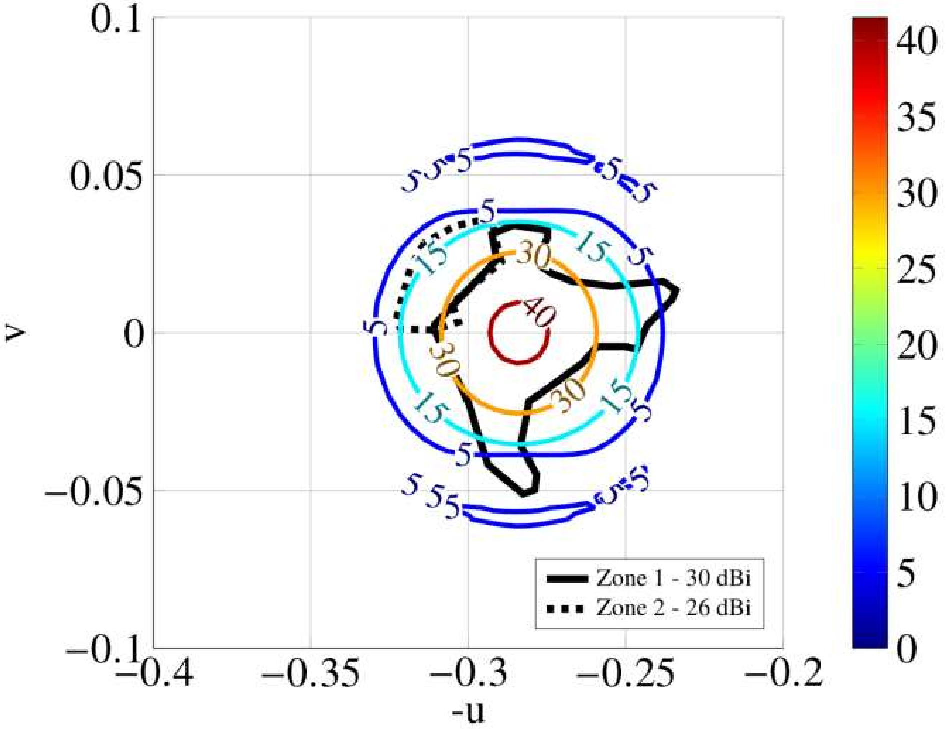
Starting point for POS

- Phase-only synthesis starting with a pencil beam:

$$\angle\rho(x_l, y_l) = k_0\left(d_l - \left(x_l \cos\varphi_0 + y_l \sin\varphi_0\right)\sin\theta_0\right)$$



Analytical phases for a pencil beam pointing at $(\theta_0, \varphi_0) = (16.5°, 0°)$.

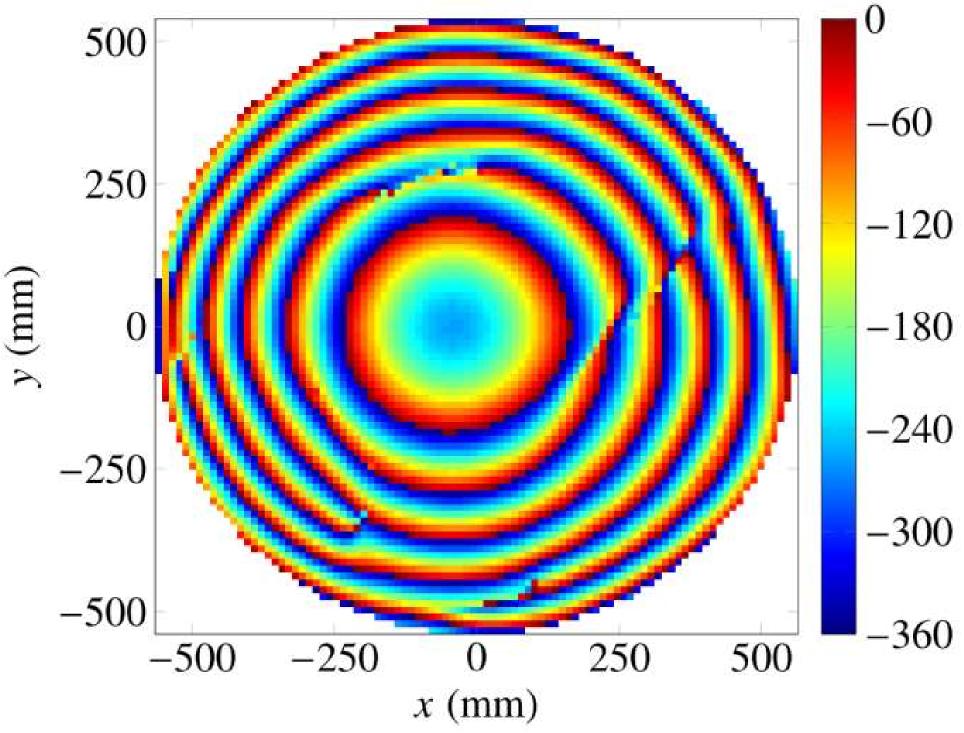


Pointing to maximum gain area.

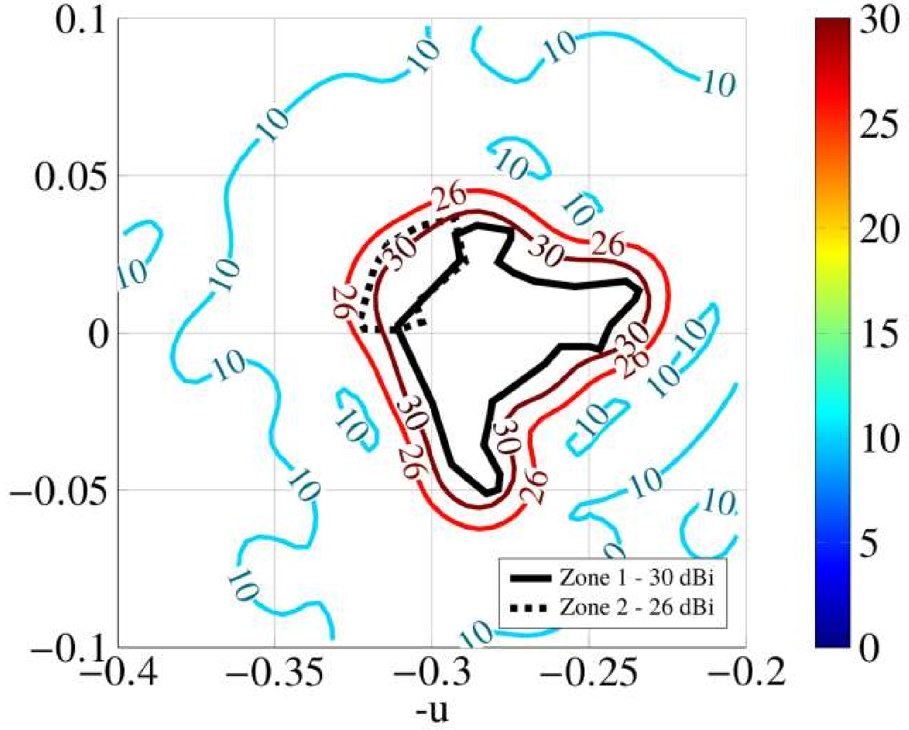
Results after POS

- Phase-only synthesis starting with a pencil beam:

$$\angle\rho(x_l, y_l) = k_0\left(d_l - \left(x_l \cos\varphi_0 + y_l \sin\varphi_0\right)\sin\theta_0\right)$$



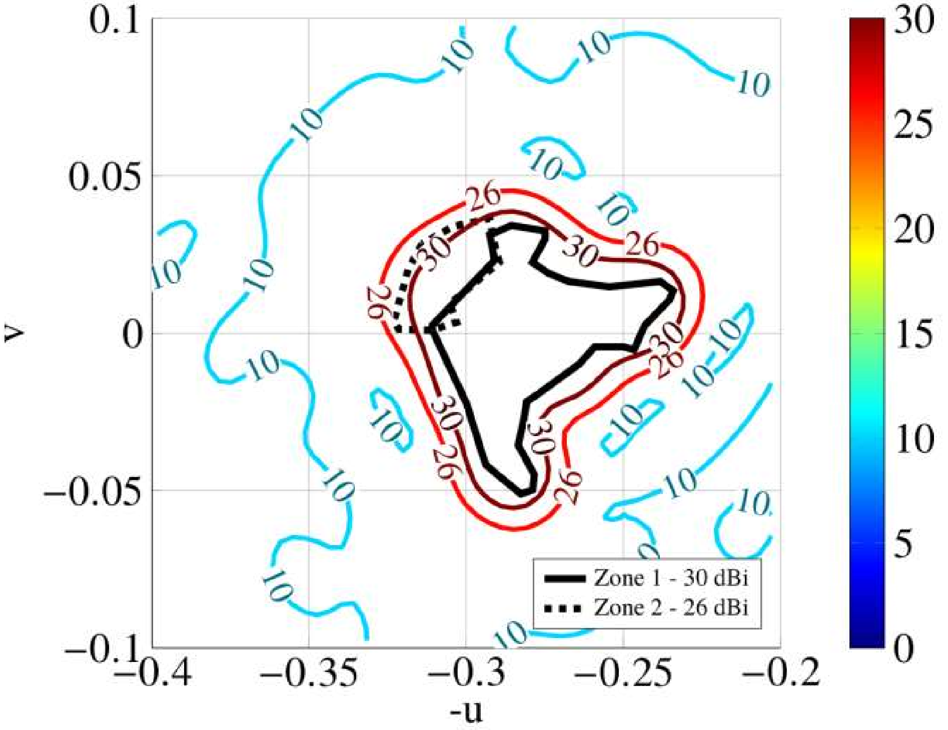
Synthesized phase-shift.



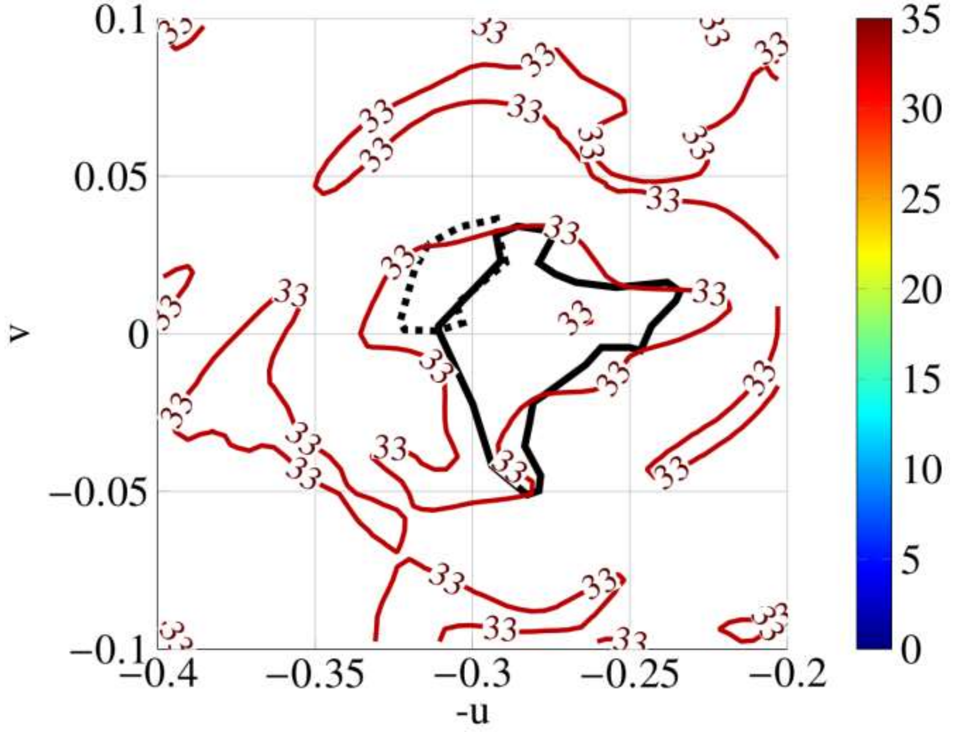
Radiation pattern after POS.

Initial design

- Initial design complies with copolar requirements at central frequency (12.50 GHz):



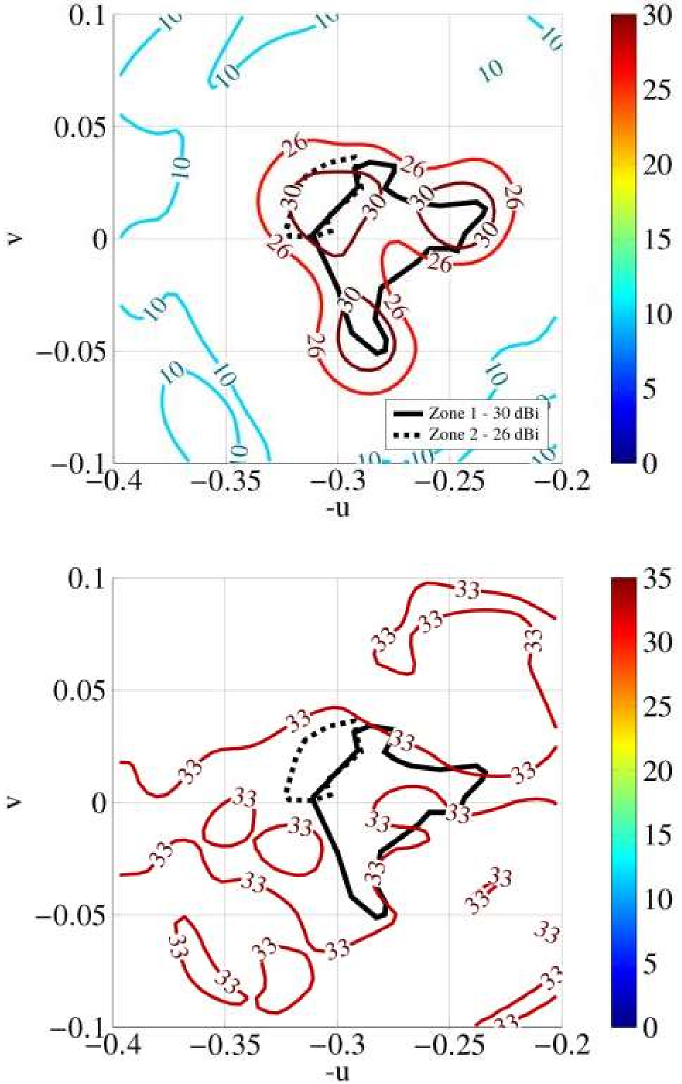
Copolar



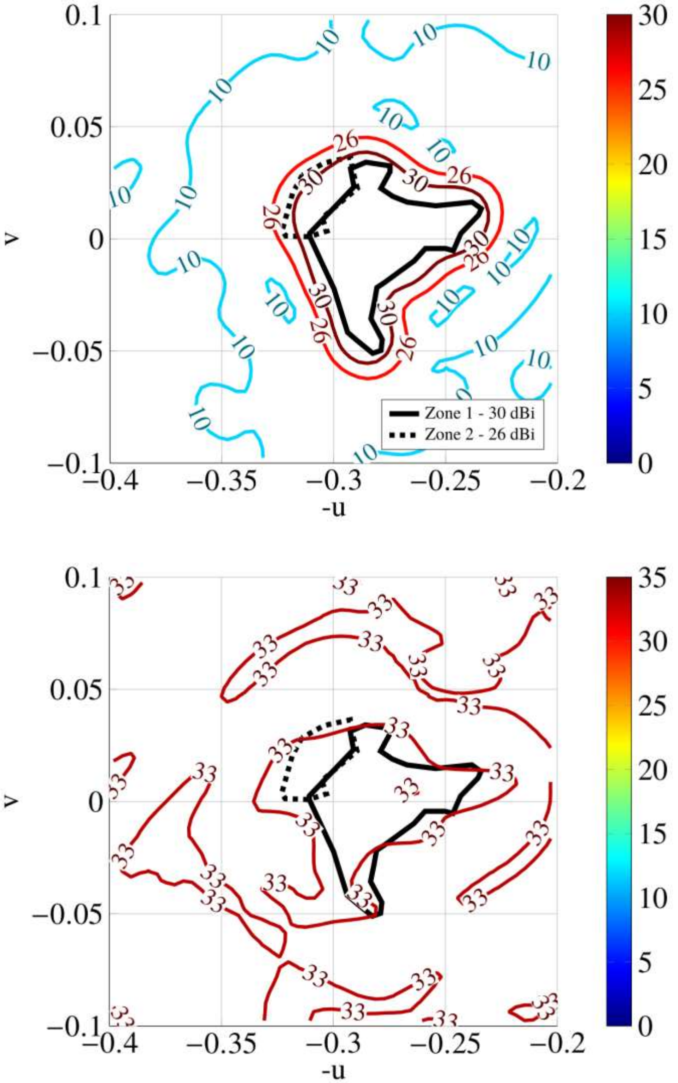
XPD

- Narrowband design.
- It does not comply with XPD_{min} at central frequency (30.4 dB).

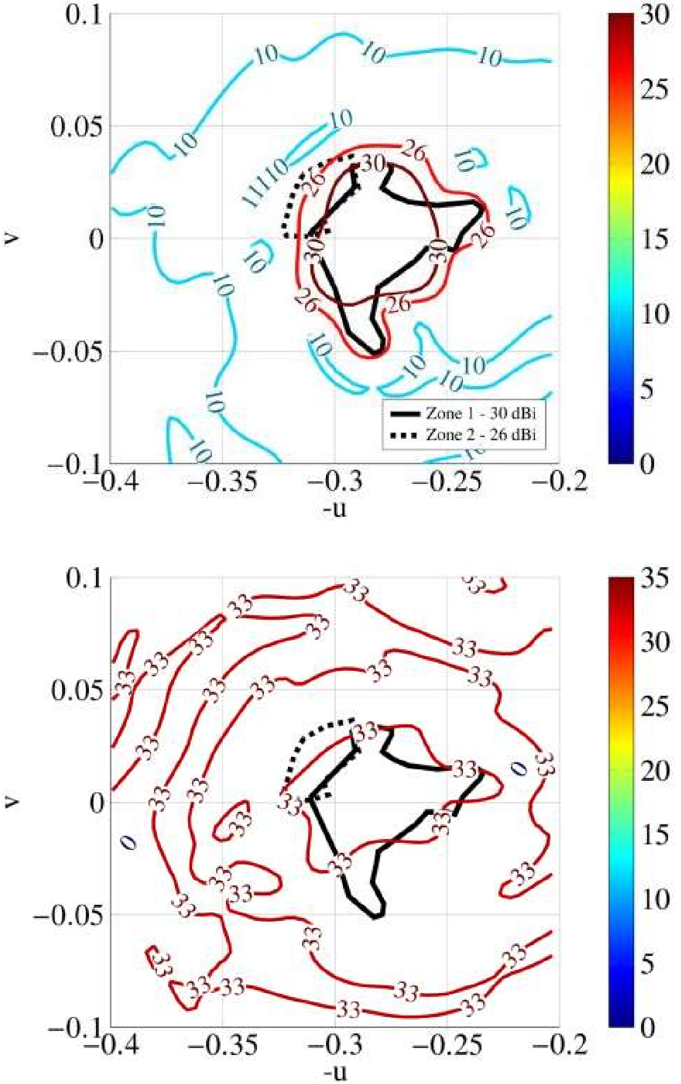
Results polarization Y at stage 1



11.80 GHz

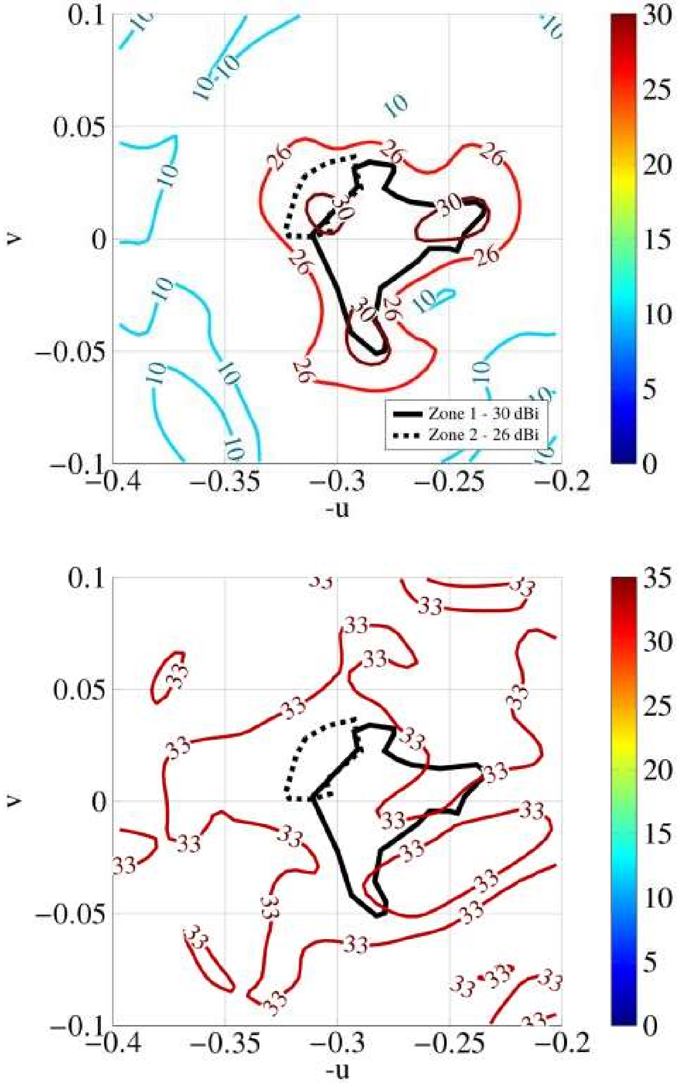


12.50 GHz

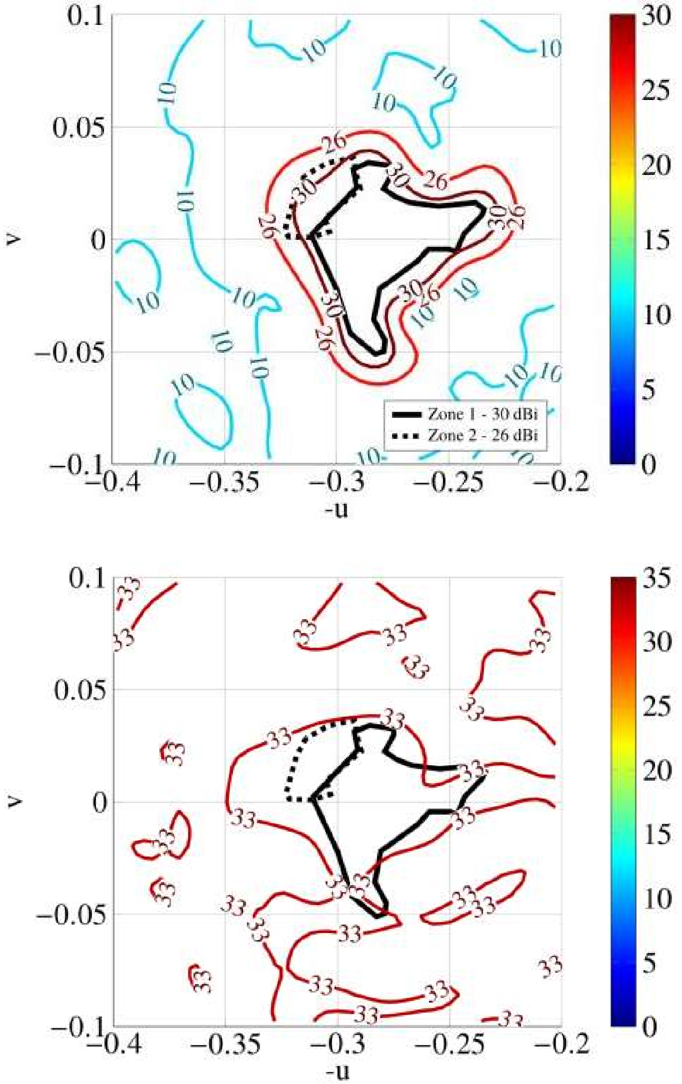


13.20 GHz

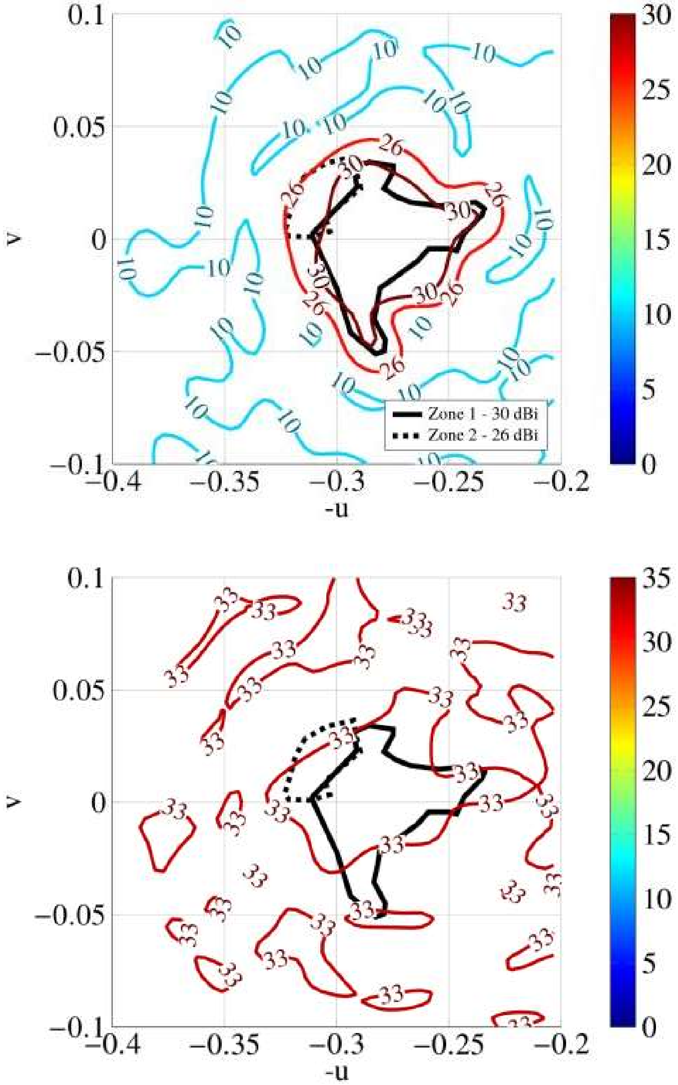
Results polarization Y at stage 2



11.80 GHz

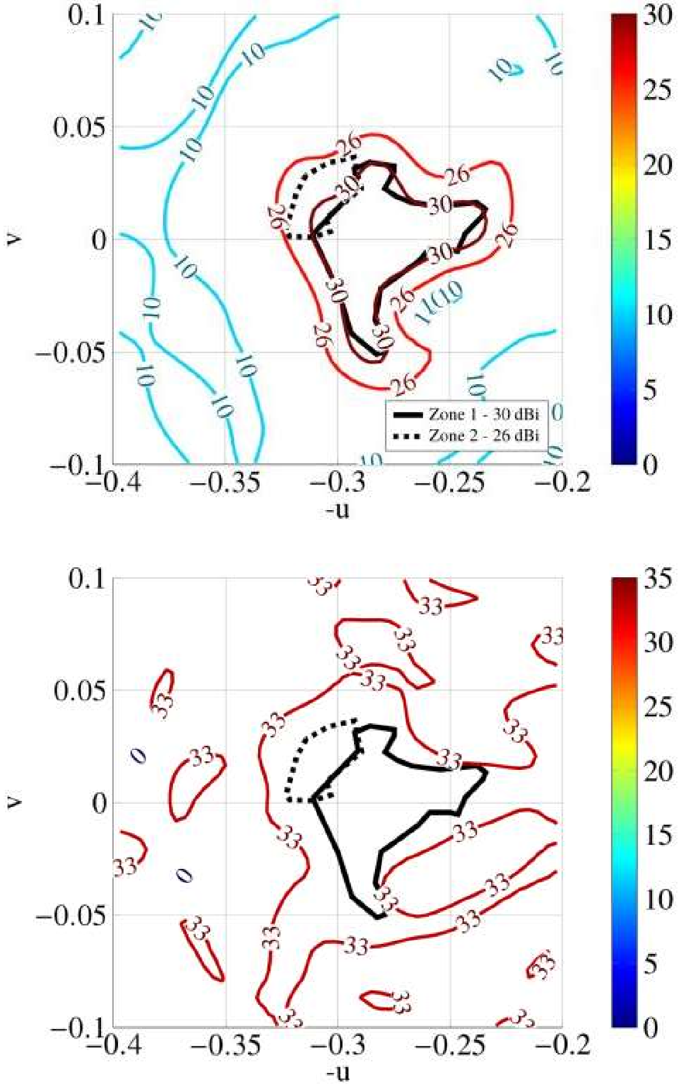


12.50 GHz

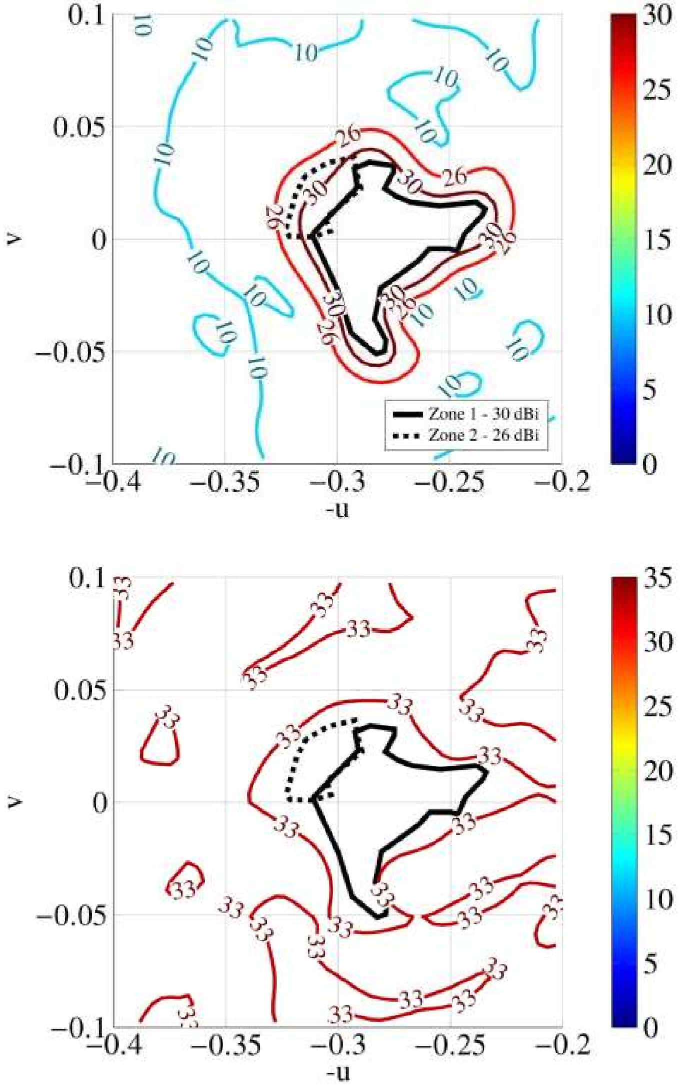


13.20 GHz

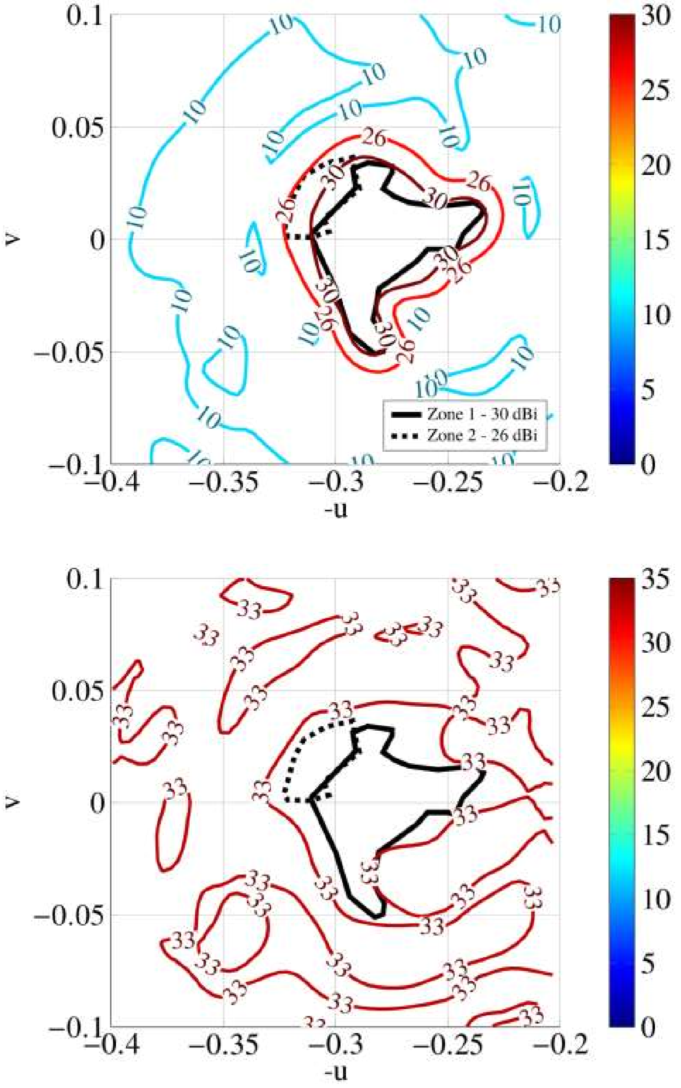
Results polarization Y at stage 3



11.80 GHz



12.50 GHz



13.20 GHz

Summary of wideband performance

		Zone 1						Zone 2					
		Polarization X			Polarization Y			Polarization X			Polarization Y		
Design	**Frequency**	**CP_{min}**	**XPD_{min}**	**XPI**	**CP_{min}**	**XPD_{min}**	**XPI**	**CP_{min}**	**XPD_{min}**	**XPI**	**CP_{min}**	**XPD_{min}**	**XPI**
Stage 1	11.80 GHz	**25.26**	**30.14**	26.75	**24.19**	**28.60**	24.94	28.65	36.15	36.03	28.79	35.25	34.69
	12.50 GHz	31.52	**32.50**	32.08	31.36	**30.51**	29.56	28.63	**32.99**	31.13	28.91	**31.76**	29.87
	13.20 GHz	**27.57**	**28.93**	26.34	**27.18**	**24.40**	22.83	**25.16**	**29.46**	26.92	**22.56**	**25.27**	23.29
Stage 2	11.80 GHz	**29.96**	**32.52**	31.65	**28.80**	**31.14**	29.50	27.86	41.72	39.93	27.58	39.27	38.29
	12.50 GHz	30.88	33.77	32.45	30.61	**31.12**	30.09	28.59	35.77	34.06	28.89	34.17	32.88
	13.20 GHz	**29.77**	**30.42**	30.40	**29.45**	**27.12**	26.60	26.70	**31.38**	29.12	26.45	**28.99**	27.56
Stage 3	11.80 GHz	30.65	37.69	37.25	30.12	34.37	33.78	27.73	42.08	41.10	26.92	38.88	38.68
	12.50 GHz	30.92	37.28	36.92	30.95	34.39	33.77	28.21	38.92	38.68	28.29	39.09	38.80
	13.20 GHz	30.68	36.77	36.31	30.46	33.00	32.68	27.24	38.82	35.91	26.94	37.11	35.98

- CP_{min} is minimum copolar gain in dBi.
- Values in red do not comply
- Compliance of 100% in CP_{min} and XPD_{min} after stage 3.

Improvement in performance

Polarization X

	Zone 1			Zone 2		
Frequency	$\mathrm{CP_{min}}$	$\mathrm{XPD_{min}}$	XPI	$\mathrm{CP_{min}}$	$\mathrm{XPD_{min}}$	XPI
11.80 GHz	+5.39	+7.55	+10.50	–0.92	+5.93	+5.07
12.50 GHz	–0.60	+4.78	+4.84	–0.42	+5.93	+7.55
13.20 GHz	+3.11	+7.84	+9.97	+2.08	+9.36	+8.99

Polarization Y

	Zone 1			Zone 2		
Frequency	$\mathrm{CP_{min}}$	$\mathrm{XPD_{min}}$	XPI	$\mathrm{CP_{min}}$	$\mathrm{XPD_{min}}$	XPI
11.80 GHz	+5.93	+5.77	+8.84	–1.87	+3.63	+3.99
12.50 GHz	–0.41	+3.88	+4.21	–0.62	+7.33	+8.93
13.20 GHz	+3.28	+8.60	+9.85	+4.38	+11.84	+12.69

- **Negative values:** zones of the initial design that complied with specifications and whose gain decreased to compensate for the improvement at other frequencies.

Conclusions

Conclusions

- A very large, broadband reflectarray for space missions has been designed.
- It works in dual-linear polarization and has enhanced cross-polarization performance.
- The design methodology is based on the generalized Intersection Approach and it is divided into several stages.
- The antenna has a southern Asia coverage and works in a 11% relative bandwidth
    - It achieves a 100% compliance in minimum copolar gain and a crosspolar discrimination better than 33 dB.

References

1. J. Huang and J. A. Encinar, Reflectarray Antennas. Hoboken, NJ, USA: John Wiley & Sons, 2008.
2. D. M. Pozar, “Wideband reflectarrays using artificial impedance surfaces,” Electron. Lett., vol. 43, no. 3, pp. 148–149, Feb. 2007.
3. E. Carrasco, J. A. Encinar, and M. Barba, “Bandwidth improvement in large reflectarrays by using true-time delay,” IEEE Trans. Antennas Propag., vol. 56, no. 8, pp. 2496–2503, Aug. 2008.
4. D. R. Prado, M. Arrebola, M. R. Pino, R. Florencio, R. R. Boix, J. A. Encinar, and F. Las-Heras, “Efficient crosspolar optimization of shaped-beam dual-polarized reflectarrays using full-wave analysis for the antenna element characterization,” IEEE Trans. Antennas Propag., vol. 65, no. 2, pp. 623–635, Feb. 2017.
5. R. Florencio, R. R. Boix, and J. A. Encinar, “Enhanced MoM analysis of the scattering by periodic strip gratings in multilayered substrates,” IEEE Trans. Antennas Propag., vol. 61, no. 10, pp. 5088–5099, Oct. 2013.
6. J. A. Encinar, R. Florencio, M. Arrebola, M. A. Salas-Natera, M. Barba, J. E. Page, R. R. Boix, and G. Toso, “Dual-polarization reflectarray in Ku-band based on two layers of dipole arrays for a transmit-receive satellite antenna with South American coverage,” Int. J. Microw. Wirel. Technol., vol. 10, no. 2, pp. 149–159, 2018.
7. “SES-12’s mission,” https://www.ses.com/our-coverage/satellites/365 [Accessed: 23 September 2019].
8. D. R. Prado, M. Arrebola, M. R. Pino, and F. Las-Heras, “Improved reflectarray phase-only synthesis using the generalized intersection approach with dielectric frame and first principle of equivalence,” Int. J. Antennas Propag., vol. 2017, pp. 1–11, May 2017.
9. D. R. Prado, J. A. Lopez-Fernandez, M. Arrebola, M. R. Pino, and G. Goussetis, “General framework for the efficient optimization of reflectarray antennas for contoured beam space applications,” IEEE Access, vol. 6, pp. 72 295–72 310, 2018.

Authors

DANIEL R. PRADO is a Post-Doctoral Research Fellow with the Group of Signal Theory and Communications, University of Oviedo (UO), Gijón, Spain. He received the B.Sc., M.Sc., and Ph.D. degrees in telecommunication engineering from the UO in 2011, 2012, and 2016, respectively. From 2011 to 2017, he was a Research Assistant with the Group of Signal Theory and Communications, UO. In 2014, he was a Visiting Scholar with the School of Electrical Engineering, KTH Royal Institute of Technology, Stockholm, Sweden. From 2018 to 2019 he was a Post-Doctoral Researcher with the Institute of Sensors, Signals and Systems, Heriot-Watt University, Edinburgh, U.K. His current research interests include the analysis of non-uniform arrays and the development of eficient techniques for the analysis and optimization of near and far fields of reflectarray antennas. Dr. Prado was a recipient of a Pre-Doctoral Scholarship financed by the Gobierno del Principado de Asturias, Spain, and a Post-Doctoral Fellowship partially financed by the European Union.

MANUEL ARREBOLA is an Associate Professor with the Electrical Engineering Department, University of Oviedo (UO), Gijón, Spain. He received the M.Sc. degree in telecommunication engineering from the University of Malaga, Málaga, Spain, in 2002, and the Ph.D. degree from the Technical University of Madrid (UPM), Madrid, Spain, in 2008. From 2003 to 2007, he was a Research Assistant with the Electromagnetism and Circuit Theory Department, UPM. In 2007, he joined the Electrical Engineering Department, UO. He has enjoyed research stays at the Microwave Techniques Department, University of Ulm, Ulm, Germany (2005); at the European Space Research and Technology Centre, European Space Agency, Noordwijk, The Netherlands (2009); at the Edward S. Rogers Sr. Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON, Canada (2018); and at the Institute of Sensors, Signals and Systems, Heriot-Watt University, Edinburgh, U.K. (2019). His current research interests include the development of efficient analysis, design, and optimization techniques of reflectarray and transmitarray antennas both in near and far fields, as well as the applicability of these antennas. Dr. Arrebola was a co-recipient of the 2007 S. A. Schelkunoff Transactions Prize Paper Award by the IEEE Antennas and Propagation Society.

MARCOS R. PINO is an Associate Professor with the Electrical Engineering Department, University of Oviedo, Gijón, Spain. He received the M.Sc. and Ph.D. degrees in telecommunication engineering from the University of Vigo, Vigo, in 1997 and 2000, respectively. During 1998, he was a Visiting Scholar with the ElectroScience Laboratory, The Ohio State University, Columbus, OH, USA. From 2000 to 2001, he was an Assistant Professor with the University of Vigo. Since 2001, he has been with the Electrical Engineering Department, University of Oviedo, Gijón, Spain, teaching courses on communication systems and antenna design. His current research interests include antenna design, measurement techniques, and efficient computational techniques applied to EM problems, such as evaluation of radar cross section or scattering from rough surfaces.

GEORGE GOUSSETIS is a Professor with the Institute of Sensors, Signals and Systems, Heriot-Watt University, Edinburgh, UK (HWU). He received the Diploma degree in electrical and computer engineering from the National Technical University of Athens, Athens, Greece, in 1998, the B.Sc. degree (Hons.) in physics from University College London, London, U.K., in 2002, and the Ph.D. degree from the University of Westminster, London, U.K., in 2002. In 1998, he joined Space Engineering SpA, Rome, Italy, as an RF Engineer. In 1999, he joined the Wireless Communications Research Group, University of Westminster, as a Research Assistant. From 2002 to 2006, he was a Senior Research Fellow with Loughborough University, Loughborough, U.K. From 2006 to 2009, he was a Lecturer (Assistant Professor) with Heriot-Watt University, Edinburgh, U.K. From 2009 to 2013, he was a Reader (Associate Professor) with Queen's University Belfast, U.K. In 2013, he joined HWU. He has authored or co-authored over 500 peer-reviewed papers, five book chapters, and one book. He holds four patents. His current research interests include microwave and antenna components and subsystems. Dr. Goussetis was a recipient of a Research Fellowship from the Onassis Foundation in 2001, the U.K. Royal Academy of Engineering from 2006 to 2011, and the European Marie-Curie Experienced Researcher Fellowships from 2011 to 2012 and from 2014 to 2017. He was a co-recipient of the 2011 European Space Agency Young Engineer of the Year Prize, the 2011 EuCAP Best Student Paper Prize, the 2012 EuCAP Best Antenna Theory Paper Prize, and the 2016 Bell Labs Prize. He has served as an Associate Editor for the IEEE Antennas and Wireless Propagation Letters.

Multi-Frequency Broadband Optimization of Spaceborne Reflectarrays for Space Applications

Daniel R. Prado[1,2], Manuel Arrebola[1], Marcos R. Pino[1] and George Goussetis[2]

[1] **Universidad de Oviedo**, Spain.
Department of Electrical Engineering. Group of Signal Theory and Comunications.

[2] **Heriot-Watt University**, UK.
School of Engineering and Physical Science. Institute of Sensors, Signals and Systems.